SCIENCE INSTITUTE DAY

AT

FERMILAB

TODAY'S THEME IS THE INTER RELATIONS
OF THE DIFFERENT
SCIENTIFIC DISCIPLINES

HERE I WILL TRY TO PRESENT THE
CORE DISCIPLINES, HOW THEY ARE
CONNECTED AND WHAT WE MEAN
BY A SCIENTIFIC DISCIPLINE

You have been lectured to on the modern biology revolution - and how various other disciplines contribute: Computer science, chemistry, physics, engineering, instrumentation etc

In this "closing thoughts" talk I would like to take you on an overview of science, examine the intellectual organization and stress the NATURE OF SCIENCE and its essential definition in terms of connections.

I. SCIENCE AND TECHNOLOGY

SCIENCE IS THE QUEST FOR KNOWLEDGE AND UNDERSTANDING

IT IS ALSO A SEARCH FOR CONNECTIONS BETWEEN THINGS THAT WOULD SEEM DISCONNECTED

TECHNOLOGY IS THE APPLICATION OF SCIENCE

E.G. LIGHTNING IS OFTEN ASSOCIATED WITH THUNDER. ARE THEY CONNECTED?

* DISEASES ARE ASSOCIATED WITH THE APPEARANCE OF BACTERIA

* CERTAIN METALLIC THINGS ATTRACT PIECES OF IRON AND HENCE WITH PHENOMENA OF MAGNET FIELD

* ELECTRIC CURRENTS ALSO PRODUCE MAGNETIC FIELDS. WHY? CONNECTION?

* WHEN DID HUMANS RECOGNIZE THE CONNECTION OF LOVE MAKING AND PREGNANCY?

ETC ETC

APPLES FALL DOWN FROM TREES AND THROWN OBJECTS RETURN TO EARTH. THE MOON CIRCLES THE EARTH IN 28½ DAYS. CONNECTION?

OCEANS AND LAKES DEMONSTRATE REGULAR TIDES SOMEHOW CONNECTED TO THE MOON. WHY?

THE SUN RISES IN THE EAST AND SETS IN THE WEST EVERY DAY WHY?

SOME "STARS" ARE FIXED, SOME WANDER WHY?

THE PLANETS ORBIT THE SUN IN THE SAME PLANE. WHY.

AS KNOWLEDGE GREW, CONNECTIONS WERE SUSPECTED, THEN ESTABLISHED. TYPES OF PHENOMENA WERE NATURALLY CLUSTERED TOGETHER.

WHITHIN THE PAST FEW HUNDRED YEARS, THERE AROSE THREE CLUSTERS OF CONNECTED PHENOMENA:

→ DISCIPLINES ←

THE PHYSICS CLUSTER

IT STARTED WITH ASTRONOMY AND SO WE STILL INCLUDE ASTRONOMY WITHIN PHYSICS ALTHOUGH THE BLENDED CONNECTION IS ASTROPHYSICS. THE GREAT BREAKTHROUGH CAME IN 1680's WITH ISAAC NEWTON WHO DISCOVERED THAT MOONS AND PLANETS MOVE FOR THE SAME REASON THAT APPLES FALL AND THE TIDES HAPPEN

THINGS MOVE SO WE MUST DEFINE AND STUDY MOTIONS (1) SPEED (2) VELOCITY (3) THE PENDULUM (4) THE STONE WHIRLED ON A STRING, A RECORD/DISK

FORCES PUSH & PULL, THEN THERE IS THE INVISIBLE BUT UBIQUITOUS FORCE OF GRAVITY
MAGNETS ATTRACT IRON - MAGNETIC FIELDS
ELECTRICAL CHARGES CREATE ELECTRICAL FORCES
eg. LIGHTNING

HEATED OBJECTS GLOW. STUDY THIS GLOW AND PATTERNS EMERGE: SPECTRA

WAVES MOVE WATER UP & DOWN BUT THE WAVE DISTURBANCE MOVES FORWARD-
WAVES MOVE AIR BACK & FORTH → SOUND

SIMILAR CONNECTED PHENOMENA ARE CLUSTERED INTO CHEMISTRY

e.g.

THE ELEMENTS

HYDROGEN
LITHIUM
HELIUM
⋮
SODIUM
⋮
URANIUM

AND WHY ARE THE ELEMENTS DIFFERENT ? ? ? ?

[THEY CAN BE LOGICALLY ORGANIZED]

- ELEMENTS CAN COMBINE INTO COMPOUNDS
- COMPOUNDS CAN REACT AND CHANGE
- GASES, LIQUIDS, SOLIDS
- CONDUCTORS & INSULATORS & THEN SEMICONDUCTORS & SUPERCONDUCTORS
- ACIDS, BASES, ELECTROLYSIS

HOW CAN IT HAPPEN THAT A VIOLENTLY ACTIVE & POISONOUS METAL: SODIUM AND A GREENISH POISON GAS: CHLORINE CAN COMBINE TO MAKE TABLE SALT?

THE BIOLOGY CLUSTER

LIVING THINGS ARE BASED ON CELLS AND CELLS ARE COMPOSED OF CHEMICAL ELEMENTS PLUCKED OUT OF THE PERIODIC TABLE OF THE ELEMENTS : CELLS MUST CHOOSE

H C N O Na F S Cl K Ca
Fe Co Ni Zn Se

WHY THESE? HOW ARE THESE SELECTED, GIVEN PRECISE LOCATIONS, GIVEN TASKS, WOVEN INTO COMBINATIONS (MOLECULES)

CHEMISTS LEARNED THE STRUCTURE OF PROTEINS, RNA, DNA BY COMBINING THE 15 OR SO ELEMENTS IN SPECIFIC SHAPES

BIOLOGY

"LIFE IS BASED ON CELLS AND CHEMISTRY GOES ON IN CELLS"

MOLECULES STORE AND DELIVER ENERGY (METABOLISM)

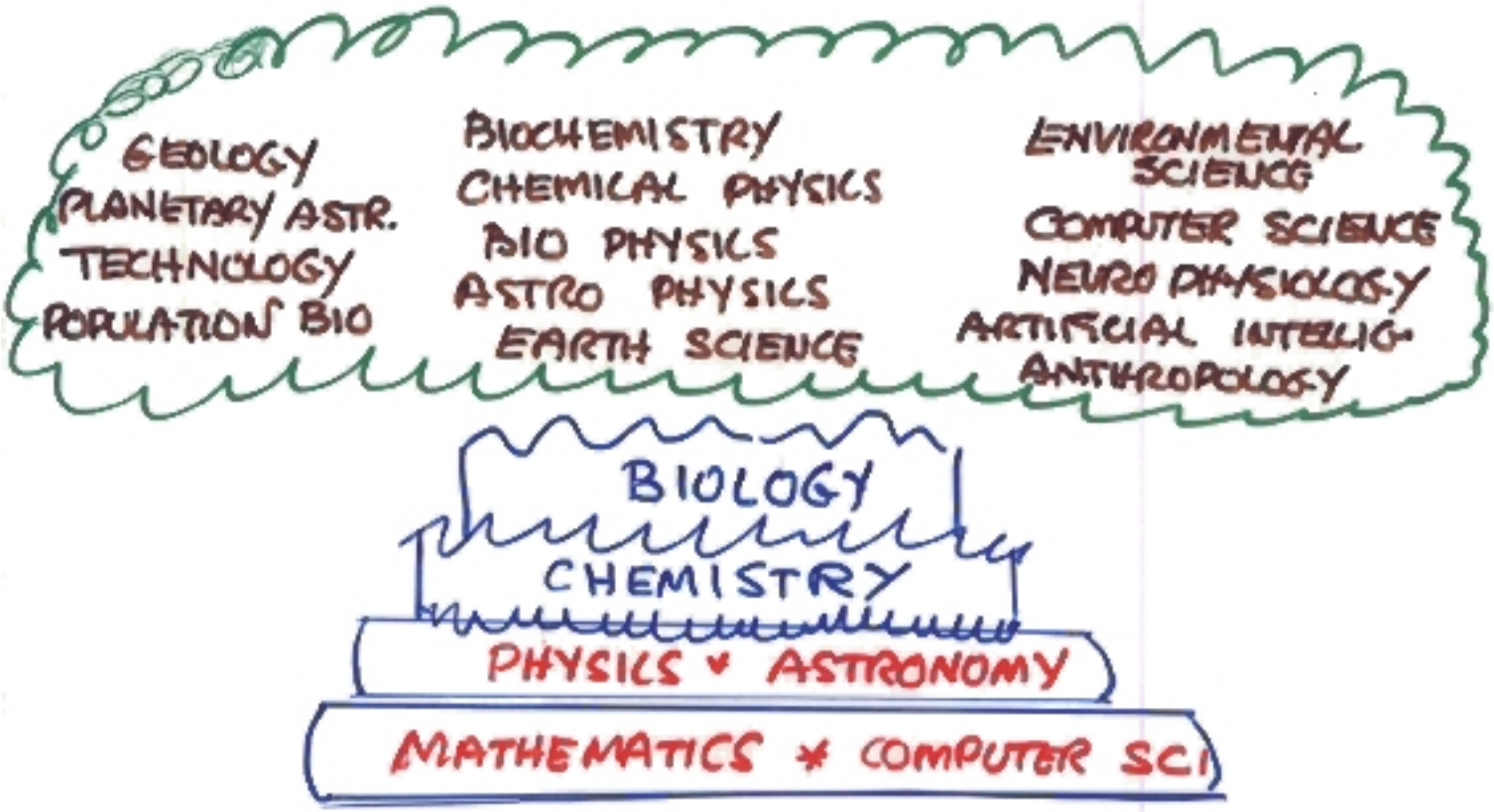
NERVE CELLS TRANSMIT ELECTRICAL IMPULSES

A SEQUENCE OF AMINO ACIDS RUNS A PARTICULAR CHEMICAL REACTION IN THE CELL ⟷ DEFINES A GENE

- ALL LIVING THINGS USE THE SAME GENETIC CODE.

EVOLUTION: CELLS SPLIT INTO TWO COMPETING INDIVIDUALS *** e.g. MUTATIONS ENABLE CELLS TO MORE EFFICIENTLY TAKE UP ENERGY-RICH MOLECULES IN THEIR ENVIRONMENT AND REPRODUCE FASTER ⇒ NATURAL SELECTION

THE THREE DISCIPLINES EVOLVED NATURALLY, LARGELY INDEPENDANTLY BUT WITH EXCHANGE OF INSTRUMENTS, WITH OVERLAPPING ISSUES AND WITH PRINCIPLES THAT EACH DISCIPLINE HAD TO OBEY.



THERE IS A HIERARCHY IN SCIENCE

Howard Gardner

Disciplines are what separates us from barbarians. I don't think you can do interdisciplanary work unhl ya have done disciplinary work.

COMMENT ON HIGH SCHOOL SCIENCE

THE EXISTENCE OF A HIERARCHY IN THE RELATIONSHIP OF THE SCIENCES IS, I BELIEVE, A PROFOUND COGNITIVE STATEMENT

PHYSICS AS THE FOUNATIONAL SCIENCE AND ITS UNIQUE ROLE IN IDEALIZATION DICTATES:

P - C - B

A YEAR OF PHYSICS GIVES STUDENTS A GOOD SENSE OF HOW SCIENCE WORKS ESPECIALLY WHEN WE INCLUDE STORIES

CHEMISTRY BROADENS THE STUDY OF MATTER AND ENERGY, DRAWING EXPLANATIONS FROM PHYSICS, AT THE SAME TIME DEEPENING THE STUDENT'S GRASP OF CONCEPTS. MORE STORIES

BIOLOGY PROVIDES A MORE COGNITIVE CHALLENGE, BUILDING ON THE CHEMISTRY AND PHYSICS THAT UNDERGIRD BIOLOGICAL ORDER

ONE OF THE INCREASINGLY POWERFUL VERTICAL TIES THAT BINDS IS MATHEMATICS

THE CONTINUOUSLY CONSUMATED MARRIAGE OF PHYSICS AND MATHEMATICS

[NOW, THE MATH POLYGAMY HAS ADOPTED CHEMISTRY, BIOLOGY, ...]

BUT ONE DOES NOT NEED ADVANCED CALCULUS TO UNDERSTAND THE CONNECTION

EG. POSITION OF A CAR (METERS)

	TIME (SEC)
X = 0	0
X = 3	1
X = 6	2
X = 9	3
X = 12	4
X = 15	5
⋮	⋮

OR

$$X = 3t$$

OR

$$\boxed{X = vt}$$ ← RAPTURE

0	0
5	1
20	2
45	3
80	4

$$\boxed{X = 5t^2}$$

PHYSICS IN CHEMISTRY

(ROALD HOFFMANN—NOBEL PRIZE CHEMIST)

"... THE DIFFRACTION OF X-RAYS, MODERN COMPUTERS AND NUCLEAR MAGNETIC RESONANCE HAVE TAUGHT US THE ARRANGEMENT OF ATOMS IN SPACE.. .. TODAY WHEN A CHEMIST THINKS OF A REACTION, HE OR SHE THINKS OF IT IN THE LIGHT OF A DOUBLE FLAME, THE MACROSCOPIC TRANSFORM-ATION (ELEMENTS → COMPOUNDS) AND THE MICROSCOPIC, MOLECULAR CHANGE. (ATOMS → MOLECULES)

NO, THESE MOLECULES ARE NOT HARD BALLS HELD TOGETHER BY STICKS, THEY ARE QUANTUM OBJECTS THAT DEMAND A DUAL VISION ... AND WE CAN PUT ENERGY INTO PARTS OF THE MOLECULE VIA AN INTENSE, MONOCHROMATIC LASER BEAM.

WHY PHYSICS FIRST?

THE KEY TO MODERN SCIENCE IS THE ATOM

"EVERYTHING IS MADE OF ATOMS"

(RICHARD FEYNMAN'S LEGACY OF THE MODERN WORLD)

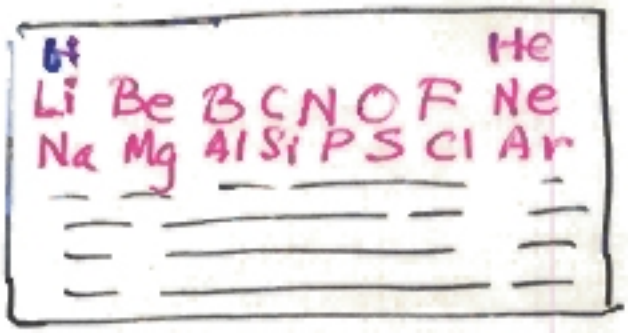
ATOMS DETERMINE THE PROPERTIES OF GASES AND LIQUIDS

ATOMIC ARRAYS MAKE CRYSTALS
MAKE SOLIDS WHICH CONDUCT ELECTRICITY
MAKE INSULATORS
MAKE SEMICONDUCTORS
MAKE SUPERCONDUCTORS

ATOMS COMBINE TO MAKE MOLECULES eg. H_2O NaCl

ATOMS EXCHANGE PLACES TO MAKE CHEMICAL REACTIONS

ATOMS DEFINE THE CHEMIST'S FLAG



LARGE MOLECULES ARE COMPLEX → BIOLOGY

MOLECULAR BIOLOGY HAS TO DO WITH GENES, CELLS, DNA, ...

Essentially all major chemical processes are explained by appeal to the properties of atoms:

Periodic Table

Chemical bond: H_2

Gas Laws

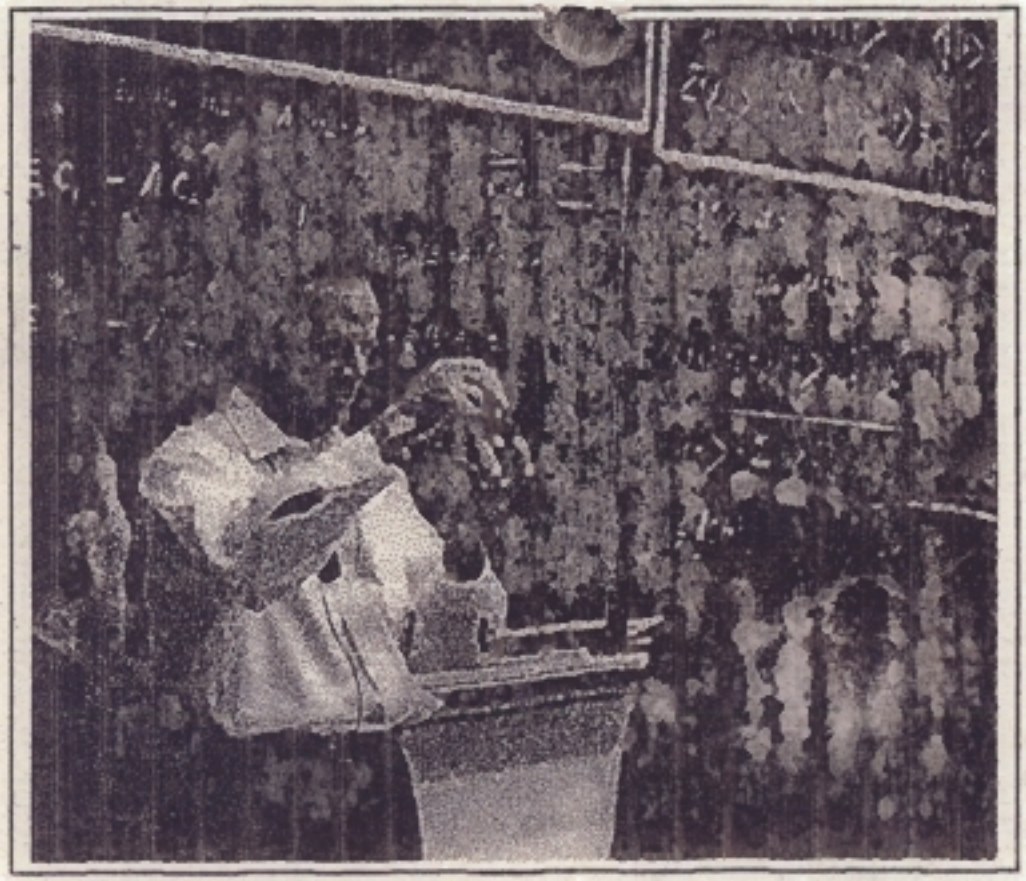
Solubility

Electrochemistry

Buckeyballs (C_{60})
(Fullerenes)

Chemical Reactions: $Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$
(e.g. battery)

STRUCTURE



Everything is made up of atoms. That is the key hypothesis. The most important hypothesis in all of biology, for example, is that everything that animals do, atoms do. In other words, there is nothing that living things do that cannot be understood from the point of view that they are made of atoms acting according to the laws of physics. This was not known from the beginning; it took some experimenting and theorizing to accept this hypothesis, but now it is accepted, and it is the most useful theory for producing new ideas in the field of biology.

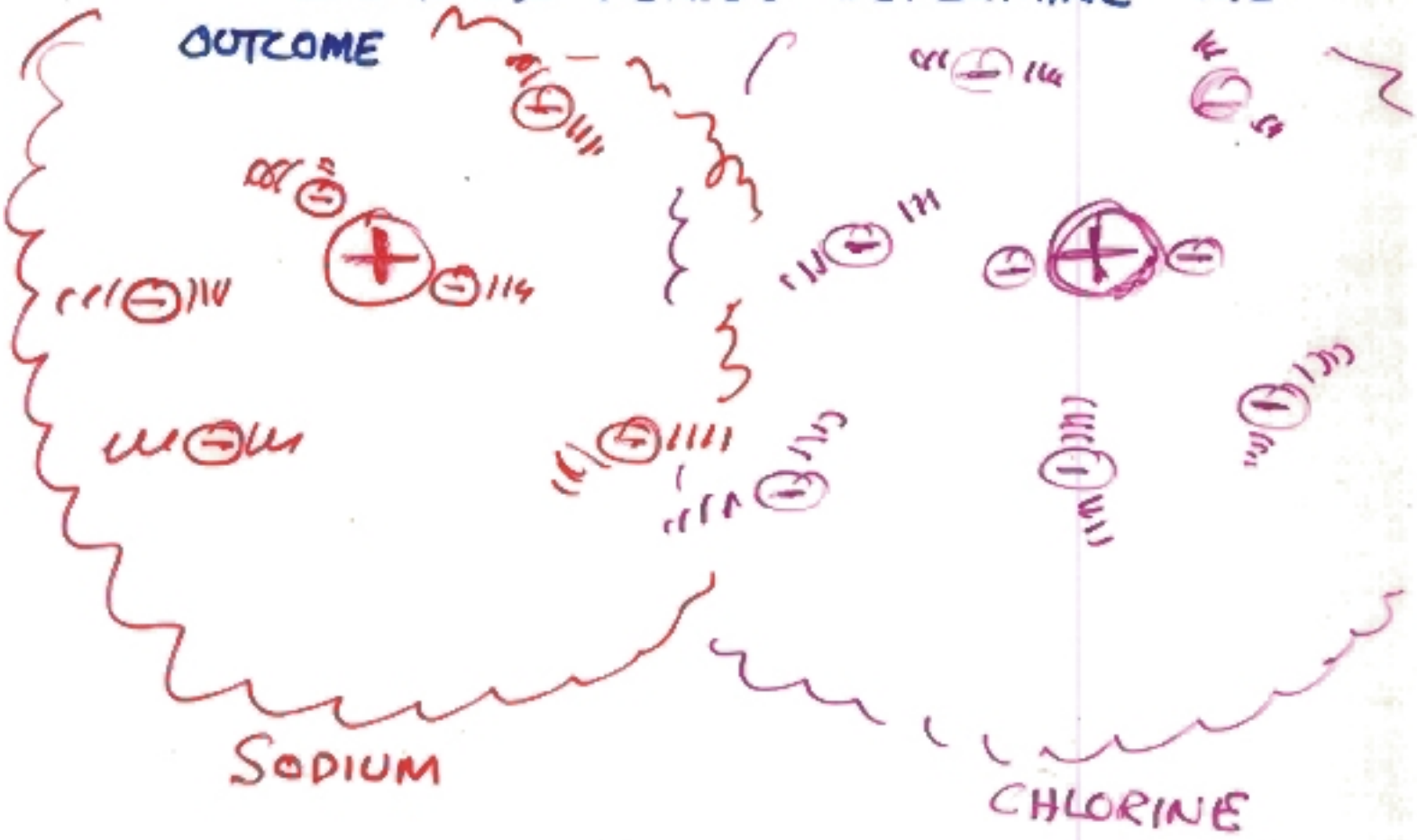
Richard Feynman (1918-1988)
Nobel Laureate in Physics, 1965

MORE PHYSICS UNDERLYING CHEMISTRY

THE "CHEMICAL BOND"

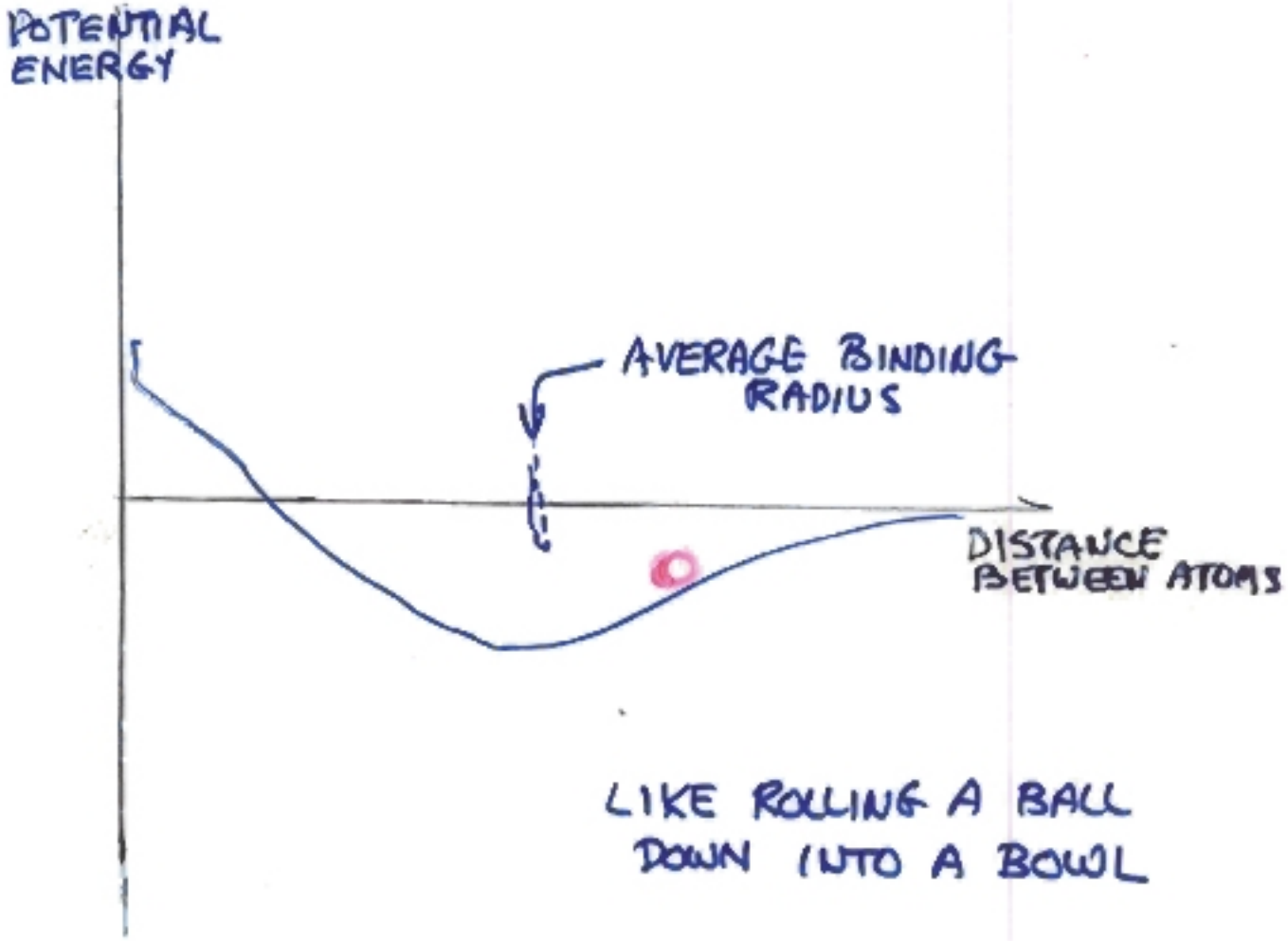
CHEMISTS SAY: TWO ELEMENTS COMBINE TO MAKE A COMPOUND

PHYSICISTS EXPLAIN: TWO ATOMS, STUFFED WITH ELECTRIC CHARGES, APPROACH AND THE ELECTRICAL FORCES DETERMINE THE OUTCOME



WHAT ENSUES IS A COMPLEX OPERATION OF COULOMB'S LAW: electrons repel electrons, nuclei attract electrons. Each particle responds to the SUM OF ALL FORCES AND THE LAWS OF QUANTUM MECHANICS. THE MATH IS SCHRODINGER'S EQN

THE PHYSICIST'S SIMPLEFICATION IS THE USE OF POTENTIAL ENERGY



LIKE ROLLING A BALL DOWN INTO A BOWL

"BINDING" IS FINDING THE LOWEST ENERGY. THE COULOMBIC FORCES, SUBJECT TO QUANTUM RULES (PAULI PRINCIPLE) DETERMINES THE FORM: IONIC, METALLIC, COVALENT.

MOLECULES CAN COLLIDE AND REARRANGE THEIR ATOMIC CONSTITUENTS ⇒ CHEMICAL REACTIONS

THE SCIENCE WAY OF THINKING

ONE OF THE MOST PROFOUND IDEAS IN PHYSICS WAS GALILEO'S LAW OF INERTIA

AN ISOLATED OBJECT WILL MAINTAIN ITS STATE OF MOTION AT CONSTANT VELOCITY FOREVER

WHY DID HE BELIEVE THIS? HOW COULD HE PROVE THIS. EVEN THE PADUA K-MART DID NOT SELL ISOLATED OBJECTS.

GALILEO'S PROOF

ONE CAN CONTINUE TO SHOW THE INTER-RELATIONSHIPS. CHEM-TO-PHYSICS. BIOLOGY TO CHEM, ALL TO COMPUTER SCI STUDENTS MOVING FROM COURSES TO DEGREES,

- SADI CARNOT - ENGINEER - PROVED ONE OF THE LAWS OF THERMODYNAMICS
- DALTON PROVED THE REALITY OF ATOMS
- MAYER BIOLOGIST ESTABLISHED CONSERVATION OF ENERGY
- FROG'S LEGS (DELICIOUS!) GAVE VOLTA THE IDEA OF BATTERY

ETC

- TIE DISCIPLINES SHARE IN THAT SCIENCE IS THE ONLY UNIVERSAL CULTURE
- SCIENCE MUST HAVE THE EXTRA-SCIENCE OBJECTIVE OF SERVICE TO HUMANITY
- SCIENCE MUST BE BASED ON OBSERVATION, SKEPTICISM, OPEN MINDEDNESS, THE VALUE OF DIVERSITY, DEEP MORAL & ETHICAL VALUES.
- SCIENTISTS MUST STRIVE FOR POPULAR SCIENCE LITERACY